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RADIO DEPARTMENT

TECHNICAL NOTE

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SecretNovember, 1944A consideration of methods of Radio Guidance
for "Little Ben"

by

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1. Abstract. Two different systems are shown to be applicable to the problem. The first system uses a homing technique and is considered to be suitable for ranges of six thousand feet air to air, and considerably in excess of this for ground to air when the new transmitters under development become available.

The second system uses a line of sight technique and is generally applicable to all rocket guidance requirements. In its simpler form the rocket equipment is relatively simple and all calculating circuits are contained at the launching site, where their performance can be checked in conjunction with the rocket trajectory, thereby considerably assisting the development work. It has the disadvantage however, that only one rocket at a time can use the guiding beam.

It is shown that a natural development of this system in which the calculating circuits are contained on the rocket is possible and any number of rockets can use the beam at once.

The relative merits of homing and line of sight are discussed from the particular application of air to air attack and it was felt that a homing system might ultimately prove to be the more accurate, although demanding a slightly larger number of circuits on the rocket.

2. Introduction. During the past few years, several rather complicated theoretical proposals have been advanced for guiding a rocket on to a target. More recently the problem has been re-examined by Instrument Department, R.A.E. who brought Radio Dept. into the problem. Preliminary considerations were given to a photo-electric method and the results are set out in an R.A.E. technical note entitled "Photo-electric attachment for Little Ben". The photo-electric guidance has now been dropped in favour of a Radio method. This Memorandum seeks to set out the considerations that have so far been given to the Radio Guidance. A certain amount of experimental work is being undertaken to check these considerations.
3. The Problem. The rocket must be guided to within a range of 200 ft. of the target at zero range. A proximity fuze can be made to fire the war head. In general the applications are as follows:-
 - (a) Air to air at ranges of 5,000 ft. or greater.
 - (b) Ground or ship to air having a range up to 15,000 ft.
 - (c) Ground or ship to air having a range up to 50,000 ft.
 - (d) Air to ship having a range greater than 5,000 ft.
 - (e) Air to ground having a range greater than 5,000 ft.

If possible the control mechanism should avoid the use of angular accelerometers or gyroscopes on the rocket due to the high accelerations

likely to be encountered in the initial stages of the rocket's flight. The rocket may carry four small wings for stabilisation and lift and aeriels can be mounted in these wings. The space available for the guiding mechanism etc. in the head of the rocket will be approximately 140 cu.inch. A calculating circuit arrangement will be necessary to convert measurement of the drift of the rocket from its true course to a form suitable for applying to the controls. It might be noted at this point that in a guided rocket the angle made by the major axis of the rocket to the line of sight is unlikely to exceed 10-15 degrees.

4. Methods of solution of the problem. The methods of solution that appear at all possible fall into two categories, viz: a homing system and a line of sight system.

The relative advantages of these systems can only be assessed after consideration of the Radio possibilities. Much of the control mechanism will be common to either Radar System employed. Several factors must however be borne in mind when considering the systems outlined in later paragraphs. These factors are:-

(a) Homing.

- (i) The difficulty on a homing system is securing adequate signal to noise level, particularly in the presence of the large amplitude of microphony likely to be present.
- (ii) In the case of a homing system the accuracy increases as the rocket nears the target.
- (iii) Selective fading of the target signal will give rise to apparent D.F. errors, which will be accentuated on applying the differential control needed for Tachometric homing. A rapid rotating beam method of D.F. is suggested and this may give some improvement.

(b) Line of sight

- (i) The automatic following of a target by Radar is not as yet smooth even when the system is on the ground as in the G.L. system. Greater variation would therefore be expected on an airborne system.
- (ii) The accuracy of a line of sight system decreases with increase in range, so that any inaccuracies in setting of the guiding beam will give rise to considerable inaccuracies at range.
- (iii) Arising from (a)(ii) to obtain accuracy the beam guiding the rocket on line of sight must be narrow and yet not so narrow as to lose the rocket in the early stages of its flight.
- (iv) Line of sight may prove to be the only suitable method for application to requirements specified in (d) and (e) of para.3.

5. Homing Solution

5.1 Pulse Technique. A Pulse transmitter is situated on the launching site and illuminates the target. This transmitter radiates pulses of some $1/3 - 1/5$ microseconds width at a high P.R.F. A P.R.F. of some 2,500 cycles would appear to be possible. On the rocket will be placed 5 antennae. Four of these will point in a forward direction. It is proposed to use Polyrod aeriels in order to provide the simplest system that will give satisfactory gain and sufficiently high directivity.

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The four antennae pointing in the forward direction will be coupled into a capacity switch. This aerial system and switch have been designed by Mr. W.A. Johnson but are not yet constructed. The design of the switch is of considerable interest in that the four aeriels are brought to a ring of circumference approximately equal to a wave length, the aeriels being tapped on at intervals equivalent to approximately 90 degrees phase angle. A rotating capacity arm picks off the signal. Rotating in synchronism with the capacity arm is a device to generate the frequency of the switch rotation. The signal received from the switch is heterodyned into an I.F. strip, is integrated at the P.R.F. frequency and the modulation produced by the switch is picked off by demodulation. The modulation frequency will be the same as that produced by the switch rotation. Now by comparing the modulation of the signal with that generated by the switch rotation, the phase angle can be found and this will give the direction of the target to the rocket in the plane carrying the minor axis of the rocket, whilst the amplitude of the modulation will give the angle made by the direction of the target to the major axis (line of flight) of the rocket. In order to compensate for distance of the rocket from the target it is desirable to apply Automatic Gain Control to the I.F. strip.

5.2 The signal strength received at 6,000 ft. with a 200 kw. pulsed transmitter on 9 cms. would appear to necessitate the use of an I.F. strip. The design of the system can now follow several variations and experimental work may be needed to determine the most suitable. In particular the back to front ratio of the antennae is uncertain so that the extent of the break through of the Illuminating transmitter cannot be accurately predicted. This may clarify the uncertainties in the choice of one of the following systems outlined in para. 5.3, 5.4, 5.5 below.

5.3 In addition to the Illuminating transmitter at the launching site, a second transmitter of similar power can be used which will radiate a signal which will be received on the rocket and used in place of a beat frequency oscillator. The frequency separation between these two transmitters will be that of the I.F. frequency of the rocket. The Beat Frequency transmitter can be triggered by the illuminating transmitter and ideally would radiate approximately $10\mu s$ pulses, starting immediately the $1/3\mu s$ pulse has been sent. The beat frequency is received on an antenna system on the rocket pointing backwards, towards the launching point.

Some difficulty may be encountered in obtaining sufficient power from the beat frequency transmission if it is radiating $10\mu s$ pulses. It is suggested in later paragraphs that the homing guidance might not take over until the rocket is some 2 or 3 thousand feet from the target. In this case the pulse width need not exceed $5\mu s$. If in fact such delayed control is applied it reduces the possibility of a break through of the direct Illuminating signal if the I.F. is inadequately biased off, as in 5.4 below.

5.4 Alternative proposal - Homing. Alternative to the proposal of para. 5.3 above, a backward looking antenna receives a keying signal sent by the second transmitter at the launching site and this may be used to trigger a beat frequency oscillator built into the rocket and/or bias off the receiver before the A.G.C. has been brought into action. A possible variation of this, however, is to operate the second transmitter at the launching site on a sub-harmonic of the beat frequency, and in place of a beat frequency oscillator on the rocket, to feed the received sub-harmonic frequency through an amplifier stage and then on to a harmonic generator. The received signal after amplification can be used to sensitise the rocket receiver. This latter system is by no means as

complicated, as might be supposed in view of the amplification now possible at say 50 cms., and has the distinct advantage that the Beat Frequency can be accurately linked with illuminating Frequency at the launching point.

5.5 Second alternative proposal - Homing. The direct radiation from the illuminating transmitter might be received either by break through on the forward looking antennae or on a backward looking antenna on the rocket and used to trigger the receiver to a state of high sensitivity in anticipation of the reflected radiation for the target. This system has the advantage that only one transmitter is used at the launching site, but has the disadvantage that the rocket in the early stages of its flight may go outside a narrow illuminating transmitter beam.

5.6 Selective fading. In the considerations of the controls on this system a difficulty arises due to the presence of selective fading which may give rise to a large differential coefficient which would possibly spoil a purely tachometric homing. It must however also be borne in mind that on a rocket of some 6 inch diameter, D/F accuracies of better than $1/2$ to 1 degree up to angles of ± 10 degrees are unlikely to be achieved. Selective fading and noise will prove most troublesome in the early stages of the rocket's flight. At later stages when the rocket is, say, less than 2,500 ft. from the target errors arising from this cause are likely to be comparable or even less than those inherent in the D/F system itself. The accuracy of control is therefore likely to improve steadily as the rocket approaches its target. In order to prevent any errors due to these causes seriously deflecting the rocket, particularly at the longer ranges, it is desirable to introduce a control which can override tachometric homing when the angle of the target to the line of flight of the rocket becomes too large. This control may be made proportional to say the cube of the angle between the target and the line of flight, and be of such a magnitude as to override the tachometric control at angles say in excess of 10 degrees.

5.7 Range on a Homing System. Ranges have been considered on this system. The gain of a Polyrod aerial can be estimated in conjunction with the proposed capacity switch, and if it assumed that a power of some 200 kw. into a 28 inch Parabola at 10 cms. is available, it would appear that an adequate signal to noise ratio can be obtained for ranges up to 6,000 ft. For ground application the probable introduction of higher powered transmitters now under development for the Admiralty, and larger parabolas should enable ranges up to 15,000 ft. to be achieved.

6.0 Homing Solution. Frequency Modulation. The possibility of using Frequency Modulation should not be overlooked. Since the direct and reflected signals may be used for producing the beat frequency no special triggering device or Beat Frequency Oscillator will be required. The transmitter as before in para. 4 would be contained at the launching source. Since only one target is involved, sinusoidal modulation can be employed. The output from the mixing stage can be passed to an A.F.

amplifier to which A.C. of suitable time constant can be applied, and the output demodulated to the switching frequency. The main disadvantages of the scheme are that it operates at zero I.F., and so is very prone to microphony and that "bonding noises" are difficult to eliminate. Nevertheless, it does offer considerable possibilities of producing a system with relatively few valves and comparatively low power consumption. A range of approximately 6000 ft. has been obtained on aircraft on this system at 80 cms. and since then the technique has been considerably improved. The primary difficulty in pushing the investigation further at this stage lies in the fact that no suitable C.W. transmitting valve which could be frequency modulated, capable of radiating some 30 watts or more, is available in production.

7.0 Line of sight solution. Transmitter on Rocket. In all line of sight solutions a complication arises due to the rotation of the rocket about its major axis. Whilst a gyroscope would solve this problem and considerably simplify the radio installation the high accelerations in the initial stages of the firing of the rocket necessitate very high workmanship and skill in obtaining the requisite balance in the gyroscope mechanism.

which does not require a Gyro,

A solution can be found, however, and in its simplest form requires a transmitter on the rocket which can be suitably modulated, or alternatively two transmitters, and a simple receiving system. Whilst on the ground a receiving system, "Calculating box" and transmitter are needed.

7.1 On the rocket is placed a transmitter feeding directly to an antenna. The transmitter can be suitably modulated in any simple manner. This transmission is D.F'd at the launching site by either a split beam system, or a rotating beam which for simplicity can be regarded as consisting of four aeriols in a parabola feeding to a rotating capacity switch. If the rotation of the rocket can be followed, linear polarisation on both the rocket and ground can be used, otherwise circular polarisation can be advantageously employed. The output from the D.F. receiver is passed to a "calculating box" which undertakes any intricate calculation necessary to guide the rocket. The output from the "calculating box" is then passed as a modulation to a transmitter. This transmitter can advantageously be a pulsed transmitter in which the P.R.F. is modulated. On the rocket is placed a simple receiver which integrates at P.R.F., picks off the modulation and passes it to the rocket controls.

7.2 The primary difficulty arises from the fact that the rocket rotates. If a gyroscope is available for the rocket, the rotation can be made to modulate the transmitter and automatic follow-up of the rotation becomes very easy.

7.3 In the case where a suitable gyroscope cannot be made available there would appear to be two solutions. The first assumes that continuous reception is maintained from the rocket. A crossed antennae system is provided at the launching point and receives the radiated linearly polarised transmission from the rocket. The signals received on each of the crossed antennae are compared in amplitude and the rotation of the rocket followed. The major difficulty of this system lies in the 180° ambiguities that are present, so that continuous follow up of the rotation of the rocket is essential. Fortunately it is not anticipated that this rotation will inherently be rapid or should it be too fast for mechanical following a certain amount of stabilisation is possible by a simple and relatively inaccurate gyroscope operating directly on a form

of aileron control. Under this arrangement the receiving antennae system at the launching point might wholly be contained in one parabola with a relatively simple transmitting aerial.

7.4 Possible use of an I.F.F. technique. An alternative arrangement of this solution is one in which a special form of I.F.F. set is placed on the rocket, the I.F.F. transmitter replacing the cw. transmitter outlined in the previous paragraph. The advantage lies in the possibility of using common antennae for transmit and receive, although a few more valve circuits will be necessary in this arrangement both on the rocket and the launching site.

7.5 Resolution of Rotation of the rocket. The second solution to the difficulty given in the first sentence of para. 7.3 offers the possibility of resolving the 180° ambiguity in the determination of the angular rotation of the rocket and at the same time removes the necessity for a continuous follow up of the rotation.

In the first instance assume that two transmitters are placed on the rocket. The first, as before, feeds into a simple antenna. The second transmitter feeds into a rotating switch which in turn feeds four antennae. This arrangement is designed to give effectively a rotating polar diagram. On the second transmitter is placed a modulation which is generated from the rotation of the switch, and which can most conveniently be frequency modulation. At the launching site the second transmission is received on a suitable aerial and the modulation obtained from the rotation speed of the switch (frequency modulation) separated from that produced by the rotating antennae (amplitude and phase). The amplitude modulation and also the phase modulation can then be measured.

On the launching site there is now available sufficient information to give the back bearing of the source as seen by the rocket and the forward bearing of the rocket as seen by the source. Comparison of the former with the differential coefficient of the latter gives the roll angle of the rocket.

There is however, an ambiguity which arises for the particular conditions when the major axis of the rocket passes through the launching point. In general this restriction is not likely to cause any marked disadvantage since there is no need to attempt to control the rocket if it is on the line of sight. If it is flying with its major axis making a constant angle with the line of sight correction for the distance it is off course will be applied; but this correction might be in error by 180° . In either case the rocket will be moved from its previous line of flight so that any errors can be immediately rectified.

7.6 Simplification of the system of para. 7.5. At first sight, the addition of this second transmitter might appear to cause more complication both to the rocket and the launching site installations than the previous system, whilst a system of interlocked pulse transmission can be envisaged; a possible simpler solution can be made on a C.W. technique. A single frequency modulated transmitter is placed on the rocket, the modulation frequency being that of an antennae switch. The output from the switch is fed to four antennae to give an effectively rotating beam. At the launching site this transmission is

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received on a rotating beam aerial system, the rotating frequency bearing no direct relationship to that of the rocket switch. The output from the launching site switch is fed to a receiver in which are separated out:- (a) the frequency modulation of the rocket transmitter, (b) the modulation produced by the effective rotation of the rocket antennae, (c) the modulation produced by the effective rotation of the D.F. antennae at the launching site, and (d) a frequency directly produced by the rotation of the D.F. switch at the launching site. The frequencies of (a) and (b) can now be compared for phase modulation, and that of (b) for amplitude modulation, whilst the frequencies of (c) and (d) can be compared for a second set of phase and amplitude modulation. A suitably designed "calculating box" can now present the correct information to a sending transmitter at the launching site for transmission to a receiving antenna on the rocket, so that the control mechanism can be operated via a simple receiver.

It will be seen therefore that this system may not result in an unduly complicated rocket or launching site assembly. Care must be exercised over reception of the required polarisation, and unwanted polarisation effects must be eliminated. The major difficulty with the system might lie in interaction between the two scanning frequencies which might result in errors in the solution of the differential equations. If the rocket frequency of "scan" can be maintained sufficiently constant these difficulties would appear to have straightforward resolution.

8.0 Line of sight solution. Receivers only on the rocket. A solution can readily be obtained after consideration of the foregoing in which only receivers are necessary on the rocket, as follows:-

8.1 In the first solution the transmitter at the launching site feeds a switched antenna system. This transmitter is suitably modulated (either P.R.F. or Frequency Modulation) to give the phase of the switching system. The switching of these antennae can preferably give the semblance of a rotating beam, or as a second alternative two crossed split beams. On the rocket are placed two aeriels at right angles. The rocket can determine its position from the phase and amplitude produced by the switched system and can follow its rotation by comparing the output from the crossed aeriels. In this case for correcting for rotation of the rocket, it would probably be easier to correct the rotational tendencies of the rocket itself rather than by any intricate mechanical follow up system. In order to determine in which direction the rocket must change its course, calculating circuits, formerly in the "calculating box" at the launching site, will now be required to be transferred to the rocket.

8.2 The alternative to the system outlined in 7.1 is to replace the receiving crossed dipoles with an effective rotating aerial system, whose speed of rotation bears no direct relationship with the rotational speed of the transmitting system. In the receiver the various frequencies are separated out as for the system outlined in para.7.5. The computation is possibly more difficult than for the system given in para.8.1 but there is no need to correct for the physical rotation of the rocket unless this proves to be simpler than the calculating mechanism.

9.0 Aerial switching speeds. It should be noted that in the beam rotational systems of para.7.5 and 8.2 the speed of switch rotation must be sufficiently fast to enable adequate smoothing to be applied before passing to the calculating circuits. The rapidity of response of the rocket to its control system determines the time that

can be taken in the calculating circuits and therefore the minimum rotational speeds. For general purposes it would appear advisable to keep the rotational speeds greater than five times that of the time constant of the control system. It is anticipated that the most rapid control system time constant will be $1/50$ sec. to $1/100$ sec.

10.0 Discussion of the foregoing systems. The relative merits of the systems proposed are not easy to assess from the standpoint of universal application, and it is most probable that the various applications will demand different systems.

For example, air to ground, air to ship, ship to ship etc. will almost certainly operate better on a line of sight system.

10.1 In both line of sight and homing Direction finding errors will be present which will cause inaccuracies in the calculating network. In the case of line of sight a D.F. error is present in automatic locking on systems and in the case of a moving launching source due also to instability of the launching base. These errors amount to $\frac{1}{2}$ a degree or more, (viz: R.E.D.E. reports on G.L.) with the rate of change of the D/F inaccuracies depending upon the type of equipment employed. The rate of change of angle will also be influenced by the stability of the launching platform. At a range of some 6,000 ft. this may become serious and an overriding "angular" correction should be applied when the actual D/F angle becomes large.

In the case of homing, a similar error is produced due to selective finding, but here it may be expected that the D.F. error becomes less appreciable as the rocket approaches the target. It may be desirable therefore in a homing system to put a time lag in the rocket receiver so that it is only brought into operation when the rocket is some 2,500 ft. from the target. Since the launching error and prediction of the target position is unlikely to be in error by more than 2 degrees the rocket will be in a position when the homing is brought into effect where the angle subtended to it by the target can be large, and yet the rocket be still sufficiently on course to make a successful homing. At this point, the rate of change of the D.F. angle will be large in comparison with the rate of change of the D.F. errors.

An additional factor likely to influence the D/F error is the vibration of the aerial system on the rocket. It is well known from experience with proximity fuses that microphony in bombs can be large, and from this it might be anticipated that the D/F system on the rocket may not be wholly free from this trouble. If the vibration frequencies are high it may be possible to smooth them out. Tests will be needed, however, to ascertain their magnitude. This disadvantage will apply equally to homing and to line of sight where D/F antennae are used on the rocket.

10.2 The size of the equipment to be carried on the rocket. The complexity of the rocket equipment might well influence the selection of any one system. It is desirable therefore to estimate for the various proposals.

(a) Homing. Since range is not required it is only necessary to amplify at the I.F. frequency until clear of microphony etc. and then to integrate to the P.R.F. where gain will be readily achieved. The equipment will consist of a four or five antennae systems, a rotating switch, Xtal rectifier, and some 14 valves. If miniature valves are used the HT power consumption will be some 80 milliamps

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at 250 volts. If midget valves are used the consumption might be lower. The equipment can be reduced to the requisite size, but may weigh about 5-6 lbs.

(b) Line of sight - Calculation on the ground.

(1) Continuous following of the rocket rotation. The equipment on the rocket would consist of a transmitting valve and a two or three valve receiver. A power consumption of 40 milliamps at 250 volts should be adequate.

(2) Automatic determination of rocket rotation. The equipment of 1(b) will be complicated by the addition of a complex antenna system, a rotating switch and possibly one more miniature receiving valve.

(c) Line of sight - calculation in the rocket. The equipment for (b)(2) above will be required together with calculating circuits. It might be anticipated that some 8-10 valves will be required with an H-T power consumption of 60 m.A. at 250 volts.

10.3 Merits of the various line of sight systems. The relative merits of the various line of sight systems are not easy to assess. It may be considered that the various systems show a gradual evolution from a relatively simple system on the rocket to a complicated one. The primary disadvantage of the simple rocket arrangement is that only one rocket at a time can be guided on the beam, but to offset this the equipment performance can be studied minutely since detailed measurements on the performance of the whole system can be checked against the dynamics of the rocket. The system in which calculating is performed on the rocket follows very naturally from the launching point equipment development, and on transposing the calculating circuits the necessity for transmission from the rocket is removed and more than one rocket can be guided simultaneously on the beam.

10.4 Note on the rotating beam. Throughout this memorandum preference has been given to a rotating beam system, over two split beams at right angles. It appears to the writer the system is likely to prove more accurate, gives a smoother control, reduces the number of valves by being able to common amplifying stages etc. and lastly has a very great advantage in making use of all four aerials at the same time to obtain the bearing, and so provides greater gain and directivity. The rotating switch now under development will be fully described later in a technical note.

10.5 Jamming. There would appear to be little to choose between line of sight and homing systems in the presence of window. The tactics to be employed by the attacking aircraft vary with the two systems, but the result is about equal on both.

In the case of a deliberate jamming transmission the line of sight may be seriously affected. Firstly the guiding beam may be deflected, secondly the jamming transmitter may break through on the aerials and produce devastating results in the control calculating circuits. In the case of homing the position is much more easy for the rocket will proceed to home on the new signal kindly provided by the target.

11.0 Conclusions and recommendations. It would appear to be certain that the guiding of a rocket can be carried out on both a homing and a line of sight principle. Experimental work is of course necessary to decide the exact technique employed. It would also appear to be desirable to work on both systems. In view of the relative simplicity

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of the line of sight in which calculation is undertaken at the launching site it would be advisable to go for this on the highest priority and thereby to determine the control characteristics for the rocket at the earliest possible date. Furthermore the system would find service application.

At the same time, on a lower priority, work should be started on Radar Homing as for air to air work. This is likely ultimately, to prove a more accurate solution than line of sight.